3D Human Big Data Exchange Between the Healthcare and Garment Sectors

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Abstract 3D personal data is a type of data that contains useful information for product design, online sale services, medical research and patient follow-up.

Currently, hospitals store and grow massive collections of 3D data that are not accessible by researchers, professionals or companies. About 2.7 petabytes a year are stored in the EU26.

In parallel to the advances made in the healthcare sector, a new, low-cost 3D body-surface scanning technology has been developed for the goods consumer sector, namely, apparel, animation and art. It is estimated that currently one person is scanned every 15 min in the USA and Europe. And increasing.

The 3D data of the healthcare sector can be used by designers and manufacturers of the consumer goods sector. At the same time, although 3D body-surface scanners

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have been developed primarily for the garment industry, 3D scanners' low cost, non-invasive character and ease of use make them appealing for widespread clinical applications and large-scale epidemiological surveys.

However, companies and professionals of the consumer goods sector cannot easily access the 3D data of the healthcare sector. And vice versa. Even exchanging information between data owners in the same sector is a big problem today. It is necessary to overcome problems related to data privacy and the processing of huge 3D datasets.

To break these silos and foster the exchange of data between the two sectors, the BodyPass project has developed: (1) processes to harmonize 3D databases; (2) tools able to aggregate 3D data from different huge datasets; (3) tools for exchanging data and to assure anonymization and data protection (based on blockchain technology and distributed query engines); (4) services and visualization tools adapted to the necessities of the healthcare sector and the garment sector.

These developments have been applied in practical cases by hospitals and companies of in the garment sector.

Keywords 3D body · Blockchain · Clothing · Obesity

1 Introduction

Three-dimensional (3D) anthropometry refers to the measurement of the human body shape. From 3D data it is possible to obtain more information than from traditional one-dimensional anthropometry, which only uses length, radius or perimeter. Anthropometry plays an important role in industrial design, clothing design and ergonomics where statistical data about the distribution of body dimensions in the population are used to optimize products. Also, changes in lifestyles and nutrition lead to changes in the distribution of body dimensions (e.g. the rise in obesity) and require regular updating of anthropometric data collections.

3D anthropometric data is a key value in scientific and economic sectors like healthcare, consumer goods and professional sports. In the past, the usage of such data was limited by the high price and low precision of 3D scanning technologies. The recent advances in scanning technologies have notoriously widened their usage opportunities. As a result, different actors from different sectors work on the generation of their own dataset of anthropometric data for their own purposes, without taking advantage of similar effort taken by other actors.

In this context, a system to share anthropometric data would allow the different data consumers access to larger datasets and also to reduce the data acquisition costs, thus augmenting their scientific or business opportunities. Besides, data holders would be able to extend the economic benefit reported by their data.

Developing an effective data sharing system is challenging. Success requires a system that gives support to interests from any participant, forming a symbiotic ecosystem. Participants in a data-sharing system can be categorized as data providers and data consumers. Regarding this categorization, the participants will have, at least, the following requirements:

- A data provider will want to preserve their data, preventing other users from replicating their dataset. Also, due to legal restrictions, a data provider may need to anonymize any data before sharing it.
- A data consumer needs to know, in detail, the type of data available at any dataset (a sort of data dictionary). The availability of tools to query for specific data (i.e. data filtering tools) is another important requirement.

The chapter relates to the technical priorities *data management* and *data protection* of the European Big Data Value Strategic Research and Innovation Agenda [1]. The BodyPass project focuses on 3D anthropometric data management and data protection. In this context BodyPass has generated tools for:

- Semantic annotation of data. BodyPass has defined an anthropometric data dictionary, or data catalogue, to accomplish seamless integration with and smart access to the various heterogeneous data sources (see Sect. 2.1).
- Templates to harmonize 3D datasets and facilitate 3D data exchange (Sect. 2.2).
- 3D anonymization tools for individual body scans (Sect. 3.1) and rules to protect privacy of health data (Sect. 3).
- Data lifecycle management with control of the data provenance with blockchain (see Sect. 4). BodyPass applies distributed ledger/blockchain technology to enforce consistency in transactions and data management.

The complete BodyPass ecosystem has been tested in practical cases described in Sects. 5 and 6.

2 The Process to Harmonize 3D Datasets

Anthropometric data has key value in many economic and social areas, among others healthcare, apparel and furniture design. The relevance of anthropometric data motivated a number of research efforts to standardize and effectively measure a human body [2–5]. But measuring a human body presents important challenges that are difficult to meet: important features such as repeatability, extrapolation of metrics or accuracy [6–9]. Some problems rely on the fact that the human body is not a rigid body, but a soft, articulated and never fully static body. Some other problems rely on the measuring tools, methodologies or different interpretations of the metric. In this context, the standardization efforts taken up to now seem to be insufficient.

The BodyPass project aims to develop a system where different actors share anthropometric data. Data sources in BodyPass belong to different sectors, currently healthcare and consumer goods sectors. As a matter of fact, this means that the measuring methodologies and measuring tools employed may differ for every dataset in the global federated database of the project. In particular, the healthcare sector data is produced by a commercial solution from Philips and is, in essence, an automatic digital measuring tape. Data from the consumer goods sector is provided by IBV and is obtained from its proprietary automatic digital measuring tape [10, 11]. As a result, all measurements in the federated BodyPass database come from digital measuring tools, meaning that there is a high risk of incompatible measurements due to the use different measuring algorithms.

In this context, the project success has required:

(a) The design and creation of an anthropometric data dictionary that clearly defines every metric. This dictionary must be open to all users and data providers, so they can validate that metrics in their databases are compatible with that in the dictionary (e.g. same metric units are employed in all databases).
(b) To agree on a common parameterization of a reference mesh so that any partner can conduct a template/model fitting process using its proprietary template and afterwards, compute the mapping between both templates. Such reference mesh can act as a kind of 'Rosetta stone' to translate body semantics between different mesh topologies and allow to build compatible body surfaces coming from different sources and parameterised with different template topologies.

2.1 The Anthropometric Data Dictionary

The anthropometric data dictionary developed in the BodyPass project is based on previous international standardization efforts from organizations such as ISO[1] or ISAK,[2] and it considers the project data consumers' requirements as well. Every metric is defined by the following fields:

- Mandatory fields:
  - ID: code that identifies the metric. It is defined as a string that partly includes the metric designation.
  - Designation: It is a self-descriptive name of the metric.
  - Definition: Unambiguous description of the metric.
  - Source: Reference to the company or organization that defined the metric. It usually refers to a standard definition.
  - Other std.: Other standard definitions that can be compatible with the metric as defined.
  - Units: Metrics units employed.
- Optional fields:

[1] International Organization for Standardization (http://iso.org).

[2] International Society for the Advancement of Kinanthropometry (https://www.isak.global/Home/Index).

ID:	WaistHeight
Designation:	Waist height (abbr Waist ht)
Definition:	Vertical distance from the waist level to the ground (virtual anthropometer). Waist level (ISO 8559-1:2017 3.1.22) is the midway level between the lowest rib point and the highest point of the hip bone at the side of the body. Lowest rib point (ISO 8559-1:2017 3.1.15) is the inferior point of the bottom of the rib cage (tenth rib) projected horizontally, 45 degrees from the mid-sagittal plane, to the surface of the skin. The highest point of the hip bone (ISO 8559-1:2017 3.1.16) is the highest point at the side of the upper border of the iliac crest.
Source:	ISO 8559-1:2017 5.1.10
Other std.:	ASTM D5219-15 Waist height, ISO 18825-2:2016 2.2.3
Units:	mm

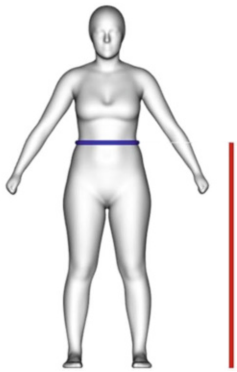


Fig. 1 Details of the definition of a metric in the BodyPass dictionary

– PartnerCodes: A List of tuples 'partner-code' where partner represents a member of the BodyPass ecosystem and code is the internal ID used on the partner's database to identify the metric.
– Media: URLs to media files (images, 3D data or videos) that facilitate metric understanding.

The BodyPass anthropometric data dictionary includes about 100 body metrics and it is available via the project's API and its web interface.[3] The web interface includes resources to access all the BodyPass API services. Among them, the resource DataResourceCatalogue [12] permits to visit the list of metrics in the project's anthropometric data dictionary. BodyPass members can use this resource to append, edit or delete metrics to/from the dictionary. In addition, the resource DataProviderMetrics lists the metrics in the dictionary supported by a given data provider. These two resources allow data consumers to consult which metrics are available in the project and also to check which data provider supports a given metric.

To facilitate the dictionary consultation to data providers, IBV lists all the metrics available in their BodyPass database, about 90 metrics, on a webpage.[4] This webpage includes an index and is far more readable than the BodyPass services deployed to this end. For every metric, the web displays the content of all the mandatory fields and also the related images in the dictionary.

Figure 1 shows the description of a metric in the aforementioned webpage. This particular metric is defined in three standardization international publications, two from ISO and one from ASTM.[5] Its definition includes two images that facilitates its understanding.

[3] http://145.239.67.20:3001/explorer/

[4] http://personales.upv.es/alrego/body/BodyPass_DigitalMeasuringTape.html

[5] American Society for Testing and Materials (http://astm.org).

2.2 3D Templates

(a) The initial approach for sharing 3D data was the use of static 3D templates agreed between BodyPass members. However, we discovered that some companies that process 3D data did not accept this approach. They thought that reverse engineering could be used for disclosing its proprietary algorithms. This problem has been solved with an innovative approach: random templates (on-the-fly templates). For this reason, BodyPass supports *standardized templates*: agreed definitions of bodies (or body parts). Standardized templates are being defined and registered in the system once and being reused in the processing of several queries. The pre-computed mapping based on one example could be used to change the 'skin' of any human surface registered with its own mesh to the reference one (or vice-versa) in a very efficient way. Upon demand by any BodyPass member, the set of agreed body part definitions can also be extended in a similar fashion as body metric definitions. In order to protect the proprietary background of BodyPass members, the topology of the released 3D content to the clients will differ from its own developed body template structure. Meaning that, prior to its delivery, data nodes will remesh or resample all 3D content hiding their own topology and parameterization.

(b) *On-the-fly templates.* The BodyPass platform defines a new template for every single data request, herein called 'on-the-fly templates'. This means to create a unique template every time the system processes a new query requiring 3D body surfaces. This strategy provides a higher protection level compared to using standardized templates by making it more difficult to conduct reverse engineering of individual data.

The procedure to manage on-the-fly templates is the following: anytime a data query arrives to the BodyPass system, a template is created on-the-fly and distributed among the processing nodes. In the next query, a new template is created and used. The template creation will provide it a random parameterization and geometry, making it unique. All the subsequent outputs from the nodes must be compliant with the template's features (namely parameterization and pose). Thus, they all can be aggregated in simple operation, i.e. weighted average of average body surfaces created by different nodes (where the weight assigned to a particular average is related to the amount of individual data used to obtain it). In summary, on-the-fly templates will be unique in terms of parameterization and geometry and will determine the parameterization, rigid alignment and pose of the query outputs, i.e., the 3D contents delivered to the client will match the template's features (Fig. 2).

3 Anonymization and Privacy

In this section, we will briefly address the solutions adopted to protect personal data. We have applied two solutions:

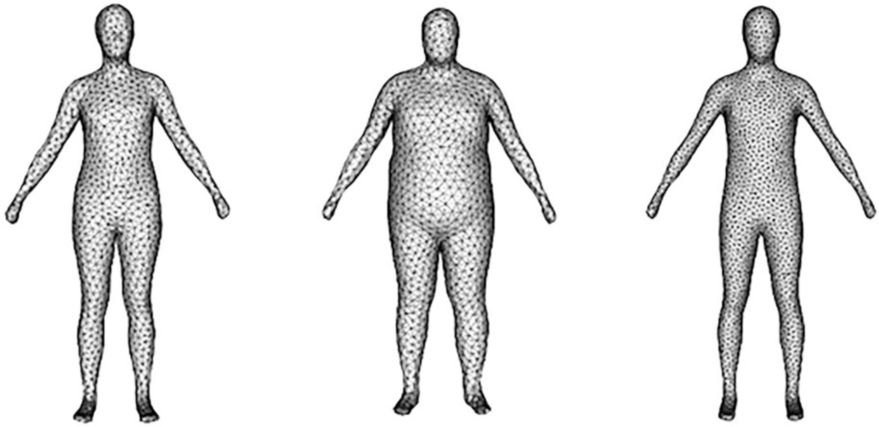


Fig. 2 Examples of on-the-fly templates with random geometry and topology (A-Pose)

(a) Anonymization of individual body scans.
(b) Architectural solution ensuring data security and privacy at hospitals with on-premise data node.

The General Data Protection Regulation (GDPR) in Europe classifies health data as sensible data, and it asks for special protection. For this reason, it was necessary to implement the architectural solution (on-premise data nodes) for processing medical images and to assure that only aggregated data is obtained from the hospitals.

3.1 The Anonymization of Body Scans

The data node of the Institute of Biomechanics (IBV) stores a database with more than 30,000 3D anonymous avatars and their related metrics. BodyPass provides tools to add new data to the database and to query and retrieve data from the database as well. This means that BodyPass's users are allowed to incorporate their own avatars to the database. To this end, the user just needs a 3D scan and basic data from the subject. During the registration of a new avatar in the database, the avatar is measured using the IBV's automatic digital measuring tape, which provides about 80 metrics from the avatar that are also stored in the database.

A basic requirement of the database is to assure the anonymization of the models. The data stored from every model includes:

- Gender, age, country, weight and height.
- The 3D avatar.
- List of metrics automatically extracted from the avatar.

From this data, the only one that can be used to identify the model is the avatar id. Given an avatar id, it would be possible to identify the model using marks on the skin (e.g. tattoos) or facial features. For this reason, avatars are stored without texture, so no skin features are stored. In this context, the face represents the only identifiable feature of the avatar.

A straightforward solution would be to remove or blur the face of the avatar, but this would end in a database full of non-human-faced avatars. This is why we considered a more sophisticated solution that incorporates a synthetic human face to every avatar.

This is performed in a three-step process:

1. The first step identifies the vertices in the raw scan that lay on the model's face.
2. Then, the identified vertices are removed, obtaining a de-faced scan.
3. Finally, the avatar registration process will add a synthetic human-looking face to the avatar.

This process presents two main challenges: The first one is to identify the vertices in the raw scan that belong to the model's face and the second is provide the avatar a human-like face. To identify the vertices which lay on the face, we use AI, in particular a convolutional neural network. The development of such a network required the exploitation of a large dataset generated in previous projects. The dataset was used to train the net and to improve its effectivity.

The computational kernel developed presents a high performance. Although the time-to-solution highly depends on the number of vertices of the input 3D object, a regular mesh of about 50,000 vertices can be processed in just few seconds. In addition, the algorithm presents a high degree of parallelism, allowing the use of massive parallel architectures like GPUs. This brings the possibility to further optimize the kernel if needed.

Once the vertices are identified, they are removed from the 3D object, obtaining a de-faced version of the raw scan.

Finally, the last step is again a challenging process that removes artifacts from the input data, including tasks as hole-filling and noise removal. This is performed via a template-fitting approach [13], which provides a realistic 3D closed avatar. This process is capable of replacing missing data, i.e. holes in the original mesh, with realistic data. In the case of the face, this means that the final avatar will have a face that will perfectly fit to the rest of the avatar and also present a human flavour (Fig. 3).

3.2 Architectural Solution Ensuring Data Security and Privacy at Hospitals

The purpose of the software installed in hospitals is twofold: extract body measurements by processing CT images and serve queries for aggregated data coming

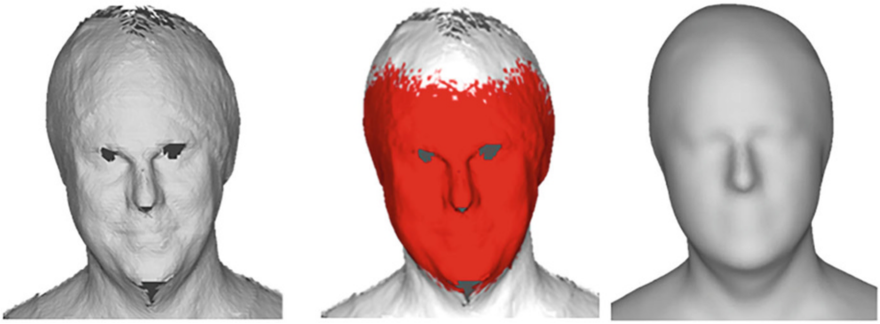


Fig. 3 Detail of the head in a raw scan (left), identification of vertices in the face (middle), synthetic face (right)

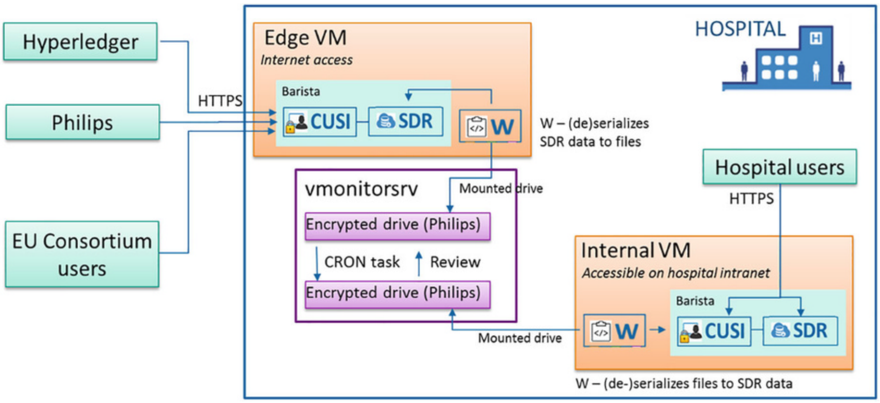


Fig. 4 Software architecture

from the Consortium users via Hyperledger. The software was created to meet the following privacy and security requirements: (1) no personal data should leave the hospital; clients outside the hospital can only receive aggregated data, resistant to de-anonymization efforts via differential privacy; (2) the server holding the personal data cannot be connected to the internet; (3) hospitals should be able to review all outgoing data; (4) no data is sent through the Hyperledger; Consortium users should be able to pick up their data directly at the hospital endpoint; (5) the derived individuals' data (e.g. measurements) is IP sensitive and therefore must be kept out of the hospital's reach, whilst also being unavailable to Philips due to privacy restrictions. Our software solution addressing the above requirements is shown in Fig. 4.

The solution requires the use of two virtual machines (VMs): 'Edge' and 'Internal'. The Edge VM has software that enables it to communicate with BodyPass members. It receives data queries from Hyperledger and makes the results available for download by users. The Internal machine is intended for the processing of raw and derived data. Due to security constraints, it operates without any connection to the internet. Every 20 s data is exchanged between Edge and Internal by means of secure bidirectional file transfers controlled by the hospital, where hospital can review all outgoing data. Both VMs use 'Barista'[6] infrastructure for storage and access to the data. Internally Barista consists of two modules. The first module is a cloud-based data repository (SDR) organized in different 'Studies' and 'Datasets', with access control capabilities. The second module is a web GUI (CUSI) for data manipulation. Datasets in the SDR are used both for the storage of derived data as well as acting as a sort of basic message passing interface for various data processing agents. This way the data processing agents are released from the implementation of their own endpoints. CUSI provides general (image) annotation and 3D visualization capabilities for the data stored in SDR.

4 The Secure Exchange of 3D Data with Blockchain

This chapter aims to describe in detail how the BodyPass approach solves the secure exchange of 3D data from a blockchain perspective. The main objective is to foster exchange, linking and re-use, as well as to integrate 3D data assets from the different business sectors. To cover this, BodyPass has adapted and created tools that allow a secure exchange of information between data owners, companies and subjects (patients and customers). In the BodyPass context, 3D personal data contains useful information for product design, online sale services, medical research and patient follow-up.

A conceptual view of the BodyPass solution is shown in Fig. 5, including the different stakeholders and main building blocks. The building blocks represent aggregated functionality, giving an idea of the flows of usage and retrieval tools.

One of the main drawbacks of the blockchain technology is the incompatibility with managing large amounts of data because of the size limitation in the transactions and the need to replicate the information in the different nodes for the consensus. To overcome this issue, we divided the BodyPass architecture into two different planes as shown in Fig. 6. The first plane depicts the data sharing itself (the Data Sharing Plane), while the second (the Data Management Plane) focuses on the management of the large data elements not so suitable to the blockchain-based plane. In addition, this modular architecture provides two key advantages: It allows scaling the number of data providers easily and facilitates additional control over the data made available by these data providers in the network and who accesses them.

[6] Barista is an integrated suite of tools, developed in Philips Research, enabling study-oriented data collection, AI algorithm creation and rapid implementation in user-facing workflows, see https://barista.eu1.phsdp.com

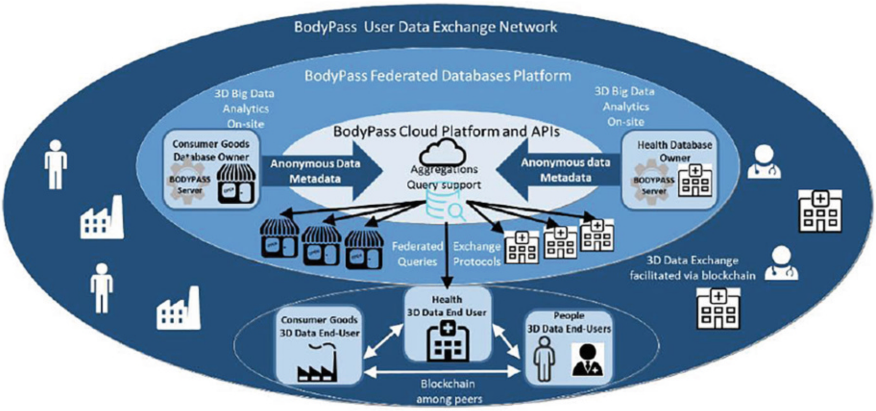


Fig. 5 High level abstraction of the BodyPass ecosystem

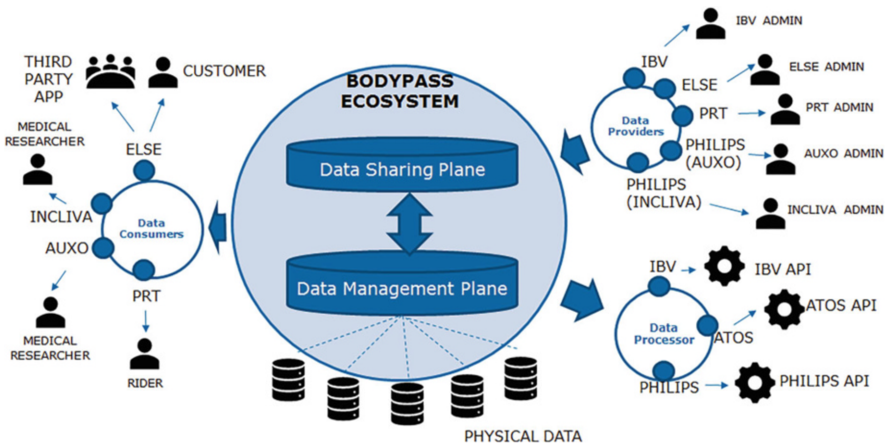


Fig. 6 BodyPass conceptual architecture

There are three different profiles that interact in the BodyPass ecosystem considering their relationship with the data: (1) data providers, (2) data processors and (3) data consumers.

Figure 6 shows these three different profiles, including examples of users of each profile with members of BodyPass.[7] BodyPass attempts to break data silos from several data providers from different sectors and foster exchange and reutilization of data assets that may help data consumers of the network to get external data. On the other hand, trust is a key aspect when devising a data sharing platform, especially if this platform is decentralized and should avoid the intervention of a central

[7] https://www.bodypass.eu/partners

authority or intermediary to certify that trust. Finally, there are several entities in the network that may generate interactions, transactions or dependencies between transactions that must also be shared in the repository. This set of characteristics led to the selection of blockchain technology [14] as the main driver of the BodyPass architecture.

The BodyPass ecosystem makes use of blockchain as a distributed ledger. Given the characteristics of the project and the business objectives, the approach selected is a permissioned blockchain, utilized by the members of BodyPass. Public blockchain networks are completely open to interact with the network and require self-governance, and private blockchain networks only allow the participation of selected entities. However, permissioned blockchain networks can adapt to hybrid scenarios like the one in BodyPass, not only letting the participants access the network once their identity has been verified but also assigning concrete permissions that can restrict which activities each participant is able to perform on the network.

Data providers usually have storage solutions for their existing assets. Therefore, the storage of the assets is not part of the scope of the blockchain in the BodyPass ecosystem. Considering these non-transactional data, which occasionally could be dynamically changed or too large, the BodyPass architecture has adopted the design pattern of off-chain storage [15], composed consequently of off-chain data (big chunks of data managed outside the blockchain network).

This approach carries some benefits, like saving bandwidth and storage capacity in the BodyPass ecosystem nodes and avoiding potential confidentiality issues derived from data being distributed out of a designated storage center. General Data Protection Regulation (GDPR) in Europe and companies doing business in Europe drive the need for new off-chain storage in blockchain applications. It is recommended to store sensitive information as off-chain data so that you can delete it if need be [16].

The *Data Sharing Plane* shown in Fig. 6 represents the implementation of the blockchain and provides the features to be a flexible trust model. It is built upon a modular architecture, configurable to choose the most suitable consensus mechanism or certification authority. There is a *Membership Service Provider* to deal with identity management and authentication. Inside the *Data Sharing Plane*, members can participate as if they were private groups by means of channels. Each member can be included in more than one channel, each of them with their own policies. All transactions are stored in the distributed ledger and, therefore, audit efficiency and quality are improved.

Due to the limitation regarding the handling of big data volumes of blockchain networks, this Data Sharing Plane is where the metadata and the permissions of the network components are managed. This has been implemented in BodyPass using Hyperledger Fabric [17] following the logic specified in the chaincode (i.e. a set of rules that govern the blockchain network) developed through the Hyperledger tool Composer [18]. Hyperledger Fabric is a permissioned blockchain network.

Considering that a building block is an asset or software piece from an architectural point of view, the BodyPass functional building blocks have interfaces to access the functionality that they provide. The green boxes shown in Fig. 7 represent

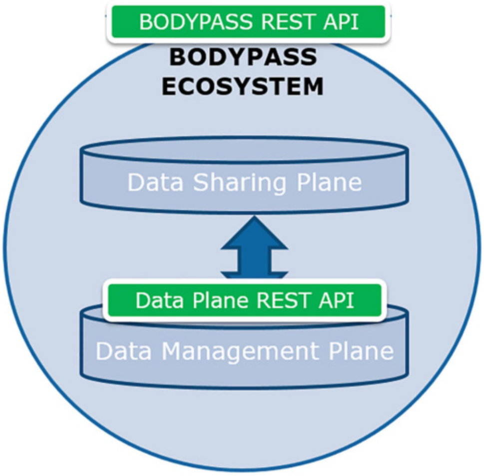


Fig. 7 BodyPass ecosystem interfaces

the implementation of these interfaces. This means both planes represented in Fig. 8 have their own API (BODYPASS REST API for the interactions with the Data Sharing Plane and a Data Plane REST API called from the Data Sharing Plane to perform the operations in the Data Management Plane).

The *Data Management Plane* exposes a REST API that will only be consumed by the *Data Sharing Plane*, and therefore the BodyPass actors do not have direct access to the Data Management plane, thus reinforcing the sense of security. Any data-related query will be executed via this API (after it has been 'authorized' and initiated in the Data Sharing Plane). The functionality of the whole ecosystem is exposed also as a REST API, in such a way the interactions with network assets, participants and transactions are available through standard HTTP operations, following the REST architecture (Representational State Transfer). This way, each HTTP request contains all the information necessary to execute it, which allows neither client nor server to remember any previous status. The interface is uniform, only specific actions (POST, GET, PUT and DELETE) are applied on the resources. As benefits, the protocol increases the scalability of the project and allows the internal components to evolve independently.

The *Data Management Plane*, as shown in Fig. 7, is the component that manages access to all off-chain data sources and orchestrates queries to be executed over the distributed storage. The Data Management Plane provides the security and required constraints for the blockchain members. Hash values are stored in order to verify the data when objects are accessed subsequently.

The Data Management Plane contains all the information supplied by the different data providers, which may be accessed for certain users of the BodyPass system who have previously reached an agreement with the data owners.

A detailed view of the Data Management Plane is shown in Fig. 8.

To access the Data Sharing plane REST API, it will be necessary to login in the system, since it is protected with an OAuth Keycloak server. The ATOS Data Hub

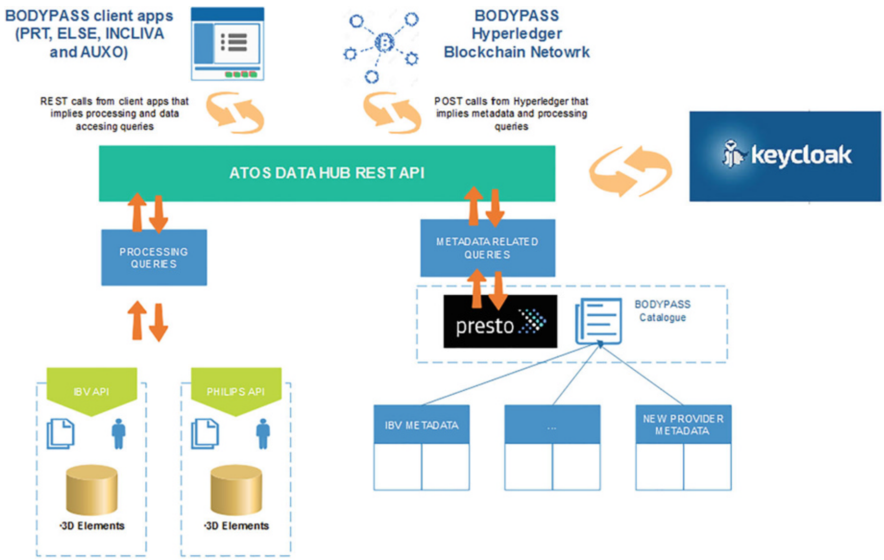


Fig. 8 Data storage plane architecture

REST API will consult the different catalogues supplied by the data providers and will obtain the necessary access information so that the user can retrieve these data. This access information is returned to the third-party application that will make the necessary call to the data providers' APIs, obtaining as a response the required information.

For the access of the blockchain network to the different data catalogs supplied by the data providers through the data plane REST API, PrestoDB [19] will be used. PrestoDB allows to perform federated queries among multiple (relational and NoSQL) databases such as Cassandra, Redis, MongoDB or PostgreSQL with a reasonable performance.

Although it has a slightly higher response time than other query engines, such as Apache Impala, it has a much more complete SQL syntax and has a longer list of database connectors (widening the scope of technologies to be used by the data providers) (Fig. 9).

The BodyPass system will generate a query plan from every request made by the user in the blockchain network. Using this query plan, PrestoDB will be able to consult the necessary data catalogs in order to obtain the necessary access information to retrieve the final data of the supplier. Figure 10 depicts the different steps taken in the application architecture in order to execute a query, showing the interaction between the different data planes and the data providers.

The query planner is the component of the BodyPass system that will be responsible for translating the requirements of the end users in queries to those catalog databases that contain the desired information, considering possible combinations between different data sources. This will be invoked through the POST

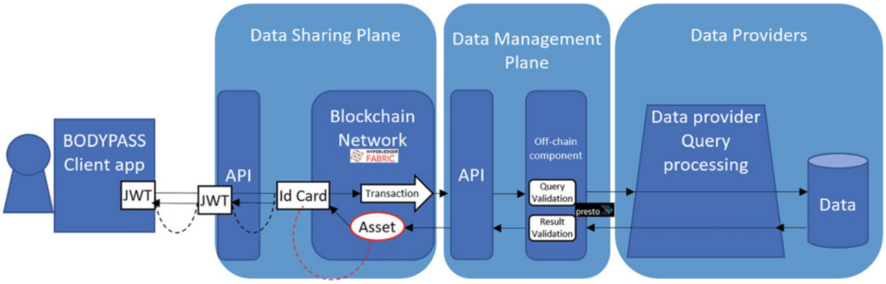


Fig. 9 Transaction data pipeline in a high-level representation of the BodyPass architecture

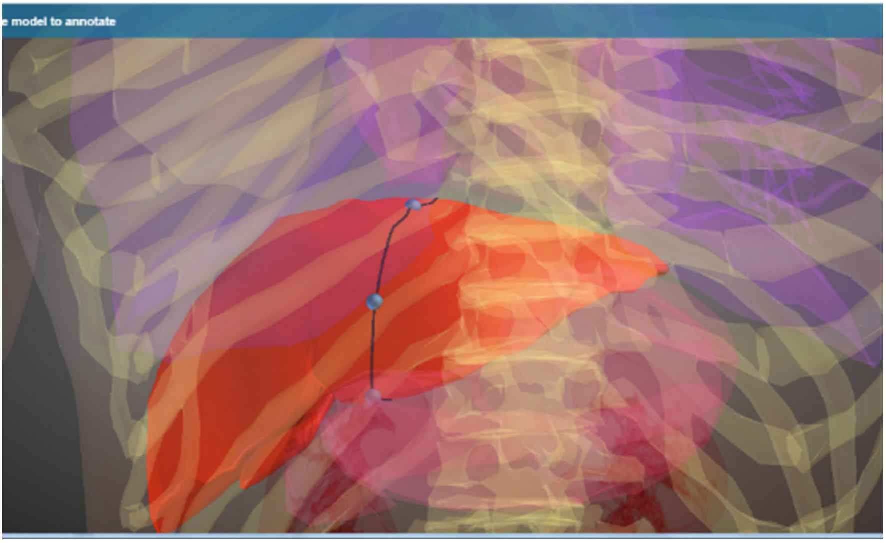


Fig. 10 Internal organ visualization and measurement

method *getQueryPlan* of the data plane REST API and used by the POST method *runFederatedQuery*.

In the case of aggregate queries, these could be directly carried out by PrestoDB for simple metrics, but it would be necessary to coordinate between 3D image processing services in the case of more complex aggregates, such as the average chest 3D scans of a certain segment of the population.

In this way, both the blockchain network and the data providers can have an exhaustive control over what information has been accessed by which user, thus facilitating monetization of data if necessary.

Finally, to conclude, it is important to note that the data sharing approach designed and implemented for the BodyPass project is accessible through the public endpoint http://145.239.67.20:3001/explorer/#/, through which an end user could access the functionalities behind the data sharing solution described in this chapter.

A Jason Web Token (JWT) will be required for accessing BodyPass endpoint in addition to a valid identity for accessing the private blockchain network that supports BodyPass. The identity will be provided by one of the existing Certification Authorities (CA) in the BodyPass blockchain private network.

5 The Application of BodyPass Results in Healthcare: Obesity

BodyPass generates tools to access huge data sets extracting useful 3D data information for assessment of body shape and its relationship to the amount of fat and body distribution. BodyPass has adapted and created tools for the secure exchange of information of 3D body shape and CT scan fat distribution.

Overweight and obesity are conditions highly prevalent worldwide, and 60% of adults in Europe meet the criteria that define these conditions [20]. Worldwide, obesity is a growing health concern. Endocrinologists treat patients who are obese because of metabolic and hormonal problems and want to provide insights into metabolic and cardiovascular disease risk [21]. The classification of obesity using BMI (Body Mass Index) does not fully encompass the complex biology of excess adiposity [22]. Obesity is closely related to metabolic risk factors and is associated with significant cardiovascular morbidity and mortality. Obese patients with metabolic abnormalities have insulin resistance, atherogenic dyslipidemia, low-grade inflammation and hypertension with a high risk to develop type 2 diabetes, atherosclerosis and cardiovascular diseases. However, not all obese subjects have these cardiometabolic abnormalities, and it is crucial to know which patients are at risk and which are not, since prognosis and therapeutic approach are different in those named Obese Healthy and Obese Unhealthy [23, 24].

The different metabolic statuses are related to fat distribution. In the Obese Healthy, fat accumulates in the subcutaneous tissue of the abdomen, around the hip and in the legs, while in the Obese Unhealthy accumulation is mainly in the mesenterium, liver, mediastinum, muscle and epicardial.

Assessment in the clinic has been the object of multiple research studies trying to properly identify measurements that predict fat distribution. Two kinds of approaches have been used, a combination of anthropometric parameters and different kinds of scans [25].

The most used among the anthropometric measurement were BMI, which indicates the presence or not of overweight and obesity but not fat distribution, abdominal circumference, waist-to-hip ratio and body shape index calculated with [WC (cm) $\times$ BMI$^{0.66}$ $\times$ height (m)$^{0.3}$]. All these parameters have the challenge of low accuracy and variability when measured in the clinic [26].

The scan methods obtain images from CT scan (Computed Tomography), MRI (Magnetic Resonance Imaging) and MRS (Magnetic Resonance Spectroscopy). The challenges of these methods is irradiation of patients, cost of the equipment, maintenance, cost of operators and time consuming. Using the BodyPass ecosystem it is possible to develop an easy, fast, accurate and inexpensive method to assess fat distribution.

Two hospitals in Italy and Spain developed a pilot with patients in order to test BodyPass, the first one includes the recording and integration of 3D Body Surface shape with data of internal fat amount and disposition in subcutaneous and visceral territories in a research environment and the second collect and transfer 3D Body Surface from a clinical environment. A summary or the pilot process is described below.

Patients recruitment was based on inclusion and exclusion criteria. This should be done in the hospital when subjects come to take CT.

Inclusion criteria: Age 19 or above, both sexes, thorax-abdominal CT and signed consent form. *Exclusion criteria:* Limitations for stand up and no signed consent form.

Data collection. In the Radiology Department a researcher recorded in a research protocol several data including:

- Demographic, clinical and anthropometric parameters to phenotype the subjects: age, gender, weight, height, BMI, waist circumference, blood pressure, personal history (diabetes, hypertension, dyslipidemia, atherosclerosis disease, other medical conditions).
- Biochemical parameters: fasting glucose, creatinine, urea, uric acid, total cholesterol, triglycerides, HDL cholesterol, AST/ALT.
- 3D scan and thoracic-abdominal CT are taken.
- Phenotype, biochemical parameters, 3D scan and CT data are gathered and stored by the researcher following the security protocol, Fig. 4.

Data integration: Integration of demographic and biochemical parameters with the results of the 3D Body Scan and CT images obtained the following data:

- Total volume of ectopic fat.
- Anatomical distribution of ectopic fat (localization).
- Total volume of VAT (Visceral Adipose Tissue) and fat in the mesenterium, liver, mediastinum, pericardium and psoas muscle.
- 3D images as an Avatar (IBV) from the subjects to explore correlation with classical clinical, anthropometric and biological parameters that are used for obesity classification and for subject's risk (BMI, waist circumference, definition of metabolic syndrome)
- Correlation of ectopic fat total volume and 3D Avatar images.

The Data Node consists of a number of software components, which, besides the extraction of measurements, also processes data queries for average measurements and body shapes, resisting data de-anonymization and providing graphical tools for exploration of the data. The software components extend the BARISTA platform which is an integrated suite of tools, developed in Philips Research, enabling study-oriented data collection, AI algorithm creation and rapid implementation in user-facing workflows; see https://barista.eu1.phsdp.com. The two components of

Barista, CUSI and SDR, have different functions. SDR is a web-based repository organized in the studies and datasets with a separate access control. SDR is used to store data within the workflow of processing individual raw data and within the data query workflow. Section 5.1 describes in more detail the workflow of processing individual raw data, extracting measurements, such as *organ fat* from data and the anthropometric data. Section 5.2 describes the workflow for processing data queries coming from the BodyPass system. CUSI is a graphical web interface that allows data manipulation, data visualization and annotation tools. Within the Data Node CUSI is used as a GUI to control the workflows, for visualization of the avatars and for annotation of the DICOM images. During the BodyPass project doctors used CUSI to define new volumes inside the parametric body for fat measurements and to get the visualization of the computed avatars.

This pilot has demonstrated that BodyPass ecosystem is a promising tool for developing new, less-invasive methods to measure fat than current ones.

Below, we describe the process for:

(a) CT image processing.
(b) Data query processing.

5.1 CT Image Processing

The primary aim of DICOM processing is to extract internal and external body measurements required by healthcare and consumer goods pilots, see Table 1.

Table 1 Body measurements

Internal measurements	FatFractionHeart, VolumeHeart, FatFractionLiver, VolumeLiver, FatFractionKidneys,[a] VolumeKideneys, FatFractionSubcutaneous,[b] VolumeSubcutaneous, VolumeBody, FatFractionPsoas, VolumePsoas, FatFractionSinus, VolumeSinus, FatFractionViceral, VolumeViceral
External measurements	HeadGirth, NeckGirth, UpperArmGirth, WristGirth, BustGirthContoured, WaistGirth, HipGirth, Mid_ThighGirth, LowerKneeGirth_Calf_, AnkleGirth, UpperArmLength, LowerArmLength, HandLength, UpperLimbLength, InsideLegHeight, HipBreadth, ShouldersLength, TrunkLength, ForearmGirth, ThighLength, CalfLength, stature
Reported in the DICOM header	Age, gender, weight, height
Low-resolution skin avatars	Full-body avatar

[a]The small size of kidney and psoas organs put high demand on the accuracy of the localization of the organs for fat and fat fraction counting, which requires further feasibility and accuracy evaluations

[b]Since raw DICOM scans are limited to thorax-abdomen scans, the measurement model of the subcutaneous volume is also limited to the thorax-abdomen area

Table 2 Different surfaces and volumes in the avatar

Body part	# Points	# Triangles	# Tetrahedrons/q5k
Full body	82, 880	106, 119	384, 868
Subcutaneous	40, 071	20, 270	219, 053
Liver	33, 034	7000	92, 785
Kidneys	30, 994	5000	179, 703
Psoas	31, 095	5000	180, 955
Lungs	36, 064	9670	213, 988
Heart	42, 122	25, 000	217, 730
Sinus	29, 923	3600	174, 238

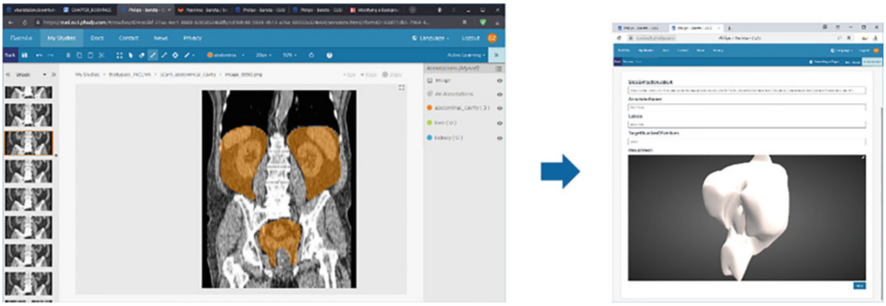


Fig. 11 Introduction of new fat measurements using BARISTA CUSI

The software relies on proprietary Philips algorithms. Since these algorithms have never been published, we can only disclose a brief outline on the underlying computations.

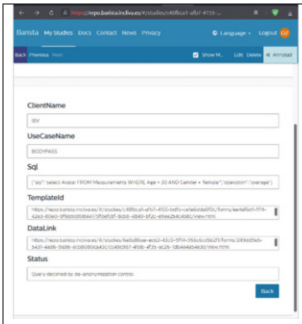
We start with pre-processing of the raw DICOM scans including automatic segmentation of some key 3D surfaces of the human body's anatomy. At the beginning of the BodyPass project, we had a choice whether to extract fat measurements directly from the CT scans, which would require to find and segment each organ of interest, or to register a 3D body avatar and use it as organ atlas. We have chosen the second approach because it allows to define and add new fat measurement locations after the avatar registration. Thus we register the volumetric 3D body avatar to the DICOM scan volume. The volumetric 3D body avatar is a graph in Euclidean space consisting, in our case, of 356,106 vertices, where neighbouring vertices are connected by 185,259 triangles and 1,937,558 tetrahedrons. Table 2 shows an example of the allocation of the avatar elements to different organs of interest.

Barista CUSI provides a collection of data annotation tools, and, amongst others, a tool for manual segmentation of slices on a reference CT scan, which can be used to define new volumes for fat measurements, see Fig. 11.

The registration process consists of two stages: at the first stage an approximate avatar is computed from the *Age, Gender, Weight* and *Height* parameters of the patient, using statistical shape models trained on about 30,000 3D scans. In the second stage the avatar is consistently refined so that the boundaries of organs on the avatar become aligned to the boundaries of the organs segmented on the DICOM image. In the initial version of the registration algorithm only three organs are automatically segmented—skin, subcutaneous volume and lungs—which limits the accuracy of the registration in smaller organs of the visceral cavity like kidney and psoas. There is ongoing work to improve the registration accuracy by adding more automatically segmented organs. The registered avatar is then used as a sort of 'atlas' to compute the local fat volumes according to the parametrically defined sampling positions. This results in the creation of 'internal' measurements. Please, note that the DICOM images are acquired in the laying pose with hands lifted up, while, according to D3.1, it is required that the measurements are collected in the standing A-pose. Therefore, an experimental algorithm was implemented that, for every registered volumetric avatar, computes another avatar in the standing pose. The external measurements are defined parametrically, as close as possible to ISO 8559-1:2017 according to the anthropometric data dictionary previously defined. This assures data harmonization with the consumer goods sector.

5.2 *Data Query Processing*

The software implements asynchronous query processing where the BodyPass system has to submit new queries, using forms to the dataset 'MeasurementQueries' in the study called 'BodyPass'; and then retrieve the same forms augmented with the query results. The avatar query forms should have filled the 'TemplateId' field with a web-link and a randomized 3D body template. The form field 'Sql' specifies the cohort selection, followed by an optional 'average' or 'regression' operator. Figure 12 shows an example query form and some possible SQL specifications. The processed form received contains a 'DataLink' pointing to the form with the query results that are stored in the dataset specified by 'UseCaseName' in the Study corresponding to the 'ClientName'.



1) {"sql":"select Avatar, Gender, Weight FROM Measurements WHERE Age > 30 AND Gender = female'", "operation":"average"}

2) {"sql":"select WaistGirth, Age, Stature, Weight, Gender FROM Measurements WHERE Age > 10", "operation":"CubicRegression", "input_feature_names":"Weight", "output_feature_names":"Age, Stature, WaistGirth"}

Fig. 12 CUSI Data query form (left), and example specifications of 'Sql' field (right)

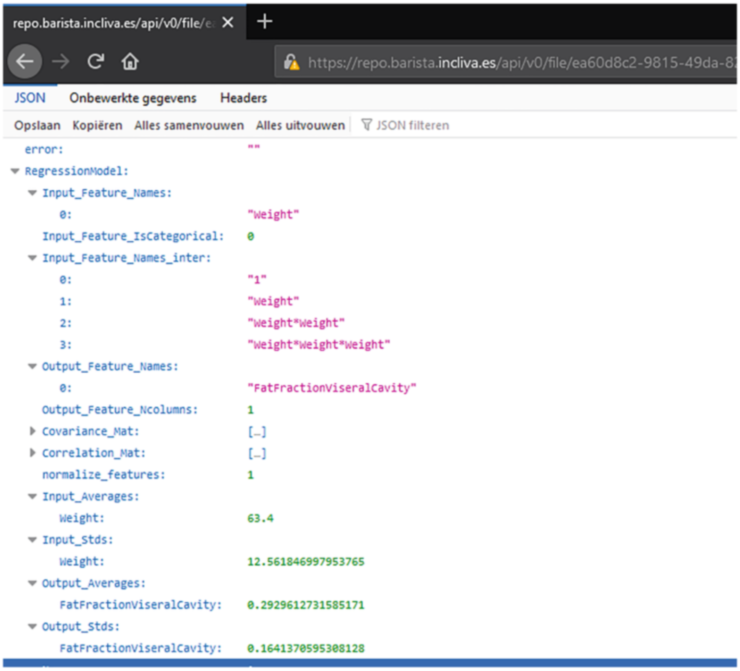


Fig. 13 The polynomial regression model

Table 3 Execution times

Operation	Time
Query transfer from 'edge' to 'internal' Barista + (de)serialization	16 s
SQL parsing (in memory active DB synchronization)	<1 s
De-anonymization control (after many queries, threshold = 10	<6 s in avg
Random template registration	<40 s
Average measurement/avatar computation	<1 s
Query transfer from 'internal' to 'edge' Barista + (de)serialization	16 s

Figure 13 shows an example response of the system for the query to compute on-premise at INCLIVA hospital the polynomial regression of the fat percentage in the visceral cavity as a function of weight.

Observe that the polynomial regression models can be easily aggregated, therefore providing opportunity for federated learning.

Table 3 shows the time required to execute different stages of the query processing, averaged over 100 queries on a data set of 37,000 records.

6 The Application of the BodyPass Ecosystem in the Apparel Industry

We describe in this section the application of the BodyPass ecosystem by two companies in the apparel industry.

P&R Têxteis S.A., founded on May 13, 1982, operates in the sector of the clothing industry, more specifically in the Apparel Sport Technical segment. Since its foundation, P&R's investment policy priorities have focused on the permanent readjustment of the Company's structure to its markets. This strategy was reflected in a constant focus on productive innovation, as well as in research and development of new innovative products that surprise the market, in differentiating factors such as quality, environment, responsiveness, flexibility and customer proximity service. P&R applies BodyPass for improving the design process of sports technical clothing.

ELSE Corp is an Italian startup that offers B2B and B2B2C solutions to brands, retailers, manufacturers and independent designers. ELSE designs and develops a Cloud SaaS platform that puts together the front-end retail processes such as product personalization and virtual 3D commerce of exclusive, personalized, possibly made to measure products. ELSE applies BodyPass for developing better online services for the apparel industry.

6.1 The Use of 3D Data for Designing Sports Technical Clothing

Sports garments require precise fitting, especially in the market segment aimed at high-performance at athletes. The traditional process needs to manufacture several prototypes until the final result is obtained: a perfect fit! The importance of this development is related to the fact that garments worn by athletes influence their performance, achievements and results.

The process of design and engineering of functional clothing design is based on the outcomes of an objective assessment of many requirements of the user, such as physiological, biomechanical, ergonomic and psychological [27]. All these requirements intensify its importance, when we are talking about high-performance athletes, such as Olympics athletes, when all the details, which could influence winning or losing by seconds, matter.

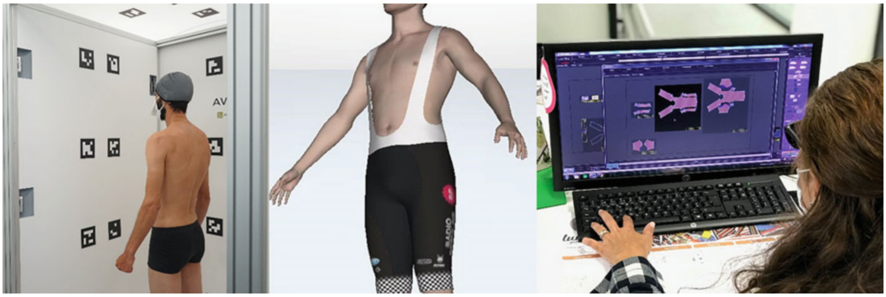


Fig. 14 Design process: scanner (left), 3D avatar (middle), pattern design (right)

For example, badly fitted clothing can cause friction and injury: loose shorts can cause drag on pedalling motions, a tight top can prevent fluid movement, among so many others. In this sense, 3D design is more than a tendency from the market, it's a need to the textile industry, among other criteria like quality and sustainability, to guarantee competitiveness in a worldwide market.

The API-Ecosystem developed by BodyPass is used for processing and exchanging 3D data in a secure manner, respecting privacy protocols. The BodyPass API's are used for:

(a) Processing the 3D data obtained with in-house 3D body scanner in order to retrieve accurate 3D human models and metrics for the development of sports garments. The 3D data obtained from BodyPass and the metrics are used by patternmaking software (Fig. 14). In this way, P&R reduces the number of prototypes needed to achieve a perfect fit for customized products is reduced, improving the efficiency of the process.
(b) BodyPass also allows access to specific 3D information from specific target consumers (e.g. by country or age), in view of the possibility to create, for example, a new collection for the segment of Winter bikewear directed to taller athletes (e.g. Northen Europe). This statistical 3D data could transmit pertinent information that will help in the development of the collection, having in concern the requirements of the market.

Looking to the future, BodyPass represents the next step in the secure transmission of 3D data between sectors, improving the ability of customization. A possibility to have access to a customer scan from the other side of the world (taken in another company) that will be used to produce an in-house garment perfectly fitting this customer, without the need for further fitting travels.

6.2 Use of 3D Personal Data in Online Services for the Apparel Industry

The apparel industry is going digital and every day more brands are joining this inevitable process. From the business and consumer point of view, traditional 2D images are becoming outdated because products are now presented and delivered digitally. Garments should be elaborated in a three-dimensional format that demonstrates the real physical properties such as material, texture, color and the product physical construction. In addition, 3D clothes are shown on realistic bodies and body parts. This makes BodyPass a crucial element of the new digital environment for the apparel industry.

BodyPass ecosystem can be made available and easily used by retail companies and tech providers. We have tested in three different scenarios how the data comes from the consumer, passes through the BodyPass ecosystem and is transformed to make it available via APIs. The processed information can be incorporated by applications such as ELSE Corp's Virtual Retail platform, which is used directly by brands.

- **Manufacturing Scenario**, also called Industrial Made to Measure: To enable companies to produce garments which are almost made to measure but still manufactured in an industrial way. This allows individual fitting by finding the most suitable items for the consumer.
- **Design Process**: To help brands and designers to create new collections by being oriented to the concrete avatars, group of people and target markets.
- **Marketing and Operations**: Reliable 3D data allows better segmentation and understanding of specific markets. The information can be used to take more accurate decisions regarding brand positioning and distribution channels.

6.2.1 Manufacturing

The apparel manufacturing process is a complex and detailed work. In the case of made to measure production, the complexity and operations increase significantly. Made to measure items must fit the persons body, and at the same time be produced together with other orders to maintain efficiency in an industrial level. The use of reliable information of body measurements allow manufacturers to create more flexible production lines. 3D data can be utilized for improved production planning and to achieve better understanding of orders placed.

Nowadays privacy is one of the most valuable assets for customers. Automation of virtual fitting on 3D body avatars in an anonymous way is one of the obligatory tasks, and BodyPass database allows to find similar bodies by measurements and create individual online orders without disclosing private information.

6.2.2 Design

In the design scenario, the BodyPass 3D anthropometric data is key. Currently, one of the most important stages of design collection creation and production is determining the size stage, which is traditionally based on statistical data. This data is often outdated because it is difficult to renew such a huge amount of statistical information in a short period of time. It represents an inconvenience for the apparel manufacturing industry, because the body parameters of the average person change more often than when the statistics are updated. Based on the dimensions of the past, the so-called "bullwhip effect" is created, when a single size range that differs significantly from reality is still used by designers. As a result, the market is overflowing with clothing that doesn't fit the potential buyer.

Based on the value created by BodyPass, it is now becoming a reality for the clothing industry to create products, which covers all parameters of the human body. It is important for producers to classify data according to different criteria (gender, age, geographical area, etc.). Updating BodyPass data regularly will be necessary because these parameters are dynamic.

Traditional body data in tables can often give the designer a blurry view of the body. But with the use of 3D modelling, it is easier for designers to understand the overall body shape and make measurements of any part of the body that is necessary for sewing a separate unit of clothing. The BodyPass technology allows not only to produce a relevant product, but to reduce the production of unsuitable clothes, creating only what will be worn.

BodyPass is not just a database of human body data. Digital analogs of the human figure can help to understand the proportions of the body. The use of BodyPass and designer's creativity together provide the ability to create a unique style based on individual characteristics of the body. The correct selection of clothing models will emphasize the advantages and provide aesthetic enhancements based on precise measurements.

6.2.3 Marketing and Operations

In the Era of Body Positivity, which focuses on challenging body standards, it becomes important for people to be able to wear clothing that will be tailored to their individual standards. This approach can increase brand positioning due to product comfort and tailored services. In addition, companies can support and execute strategies based on personalized made to measure items. This can act as a communication tool to refresh brand positioning and enhance customers' perception.

Creating clothes according to individual requirements is a trend that has been around for years already. Examples there are many, from luxury brands that have offered made to measure services along their history, to more affordable brands that have democratized product customization. In fact, according to Deloitte [28], on average 36% of consumers expressed an interest in purchasing personalized products or services. Nowadays it is possible to save the parameters of body types and measurements for future use, and thanks to 3D modeling brands are able to modify collections according to the figure of a specific person or market, producing products that fit perfectly without compromising any of its features.

By getting statistical data about body measurements, it is possible to reduce costs because knowing the exact size stage, brands can buy the necessary amount of materials. After adjusting some necessary parameters (height, chest, waist, etc.) and using 3D modeling as a tool, the perfect collection for a market can be created and sent to production. Another advantage that 3D data offers is the possibility of segmenting orders by body type and regions, which enables businesses to optimize their distribution channels and to reduce transportation and warehouse costs.

Nowadays e-commerce represents an essential revenue stream for businesses around the world. Even though online sales are already a developed form of retail, there are still disadvantages specially for products that have a measure for fitting. Sizing issue is a reason for shoppers returning online orders. According to a research performed by Global Web Index in the USA and UK, 52% of people had to return an item because the fit was not right and they could not try it on before they bought it [29]. The use of avatars and anthropometric data segmented by range of age and country could solve the fitting problem for online retailers.

The benefits of a reliable database of body measurements do not stop there. The information can be utilized to develop better shipping and return policies. Almost 50% of online shoppers buy multiple sizes of a product in order to ensure the right fit [30]. In addition, 14% of customers buy items they don't need so they could qualify for free shipping, with the intention of returning them after [29]. In the US alone, a more accurate size segmentation and access to reliable data, could help online retailers to reduce return expenses for more than US$107 billion lost yearly [31].

Thus, the usage technology of BodyPass in online services for the apparel industry will contribute to the digital transformation of the fashion industry, optimizing production process, reducing costs and waste.

7 Conclusions

BodyPass has developed an ecosystem of APIs and tools that allow the exchange of 3D anthropometric data that preserves IP rights and personal privacy. This is achieved through the use of:

- Semantic data annotation with a data dictionary compatible with ISO and CEN (European) standards.
- GDPR compliance with the use of tools that create anonymous synthetic data in 3D, the implementation of an architectural solution in hospitals that guarantees additional protection to sensitive data and the use of off-chain storage blockchain.

BodyPass ecosystem offers a novel approach for effective data sharing of 3D human data between data silos. The tools developed in BodyPass contribute specifically to two of the technical priorities defined in the framework of the European Big Data Value Strategic Research and Innovation Agenda: data management and data protection.

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